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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

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NAVAL FACILITIES ENGINEERING COMMAND

AIR LEAKAGE MEASUREMENTS IN NAVY
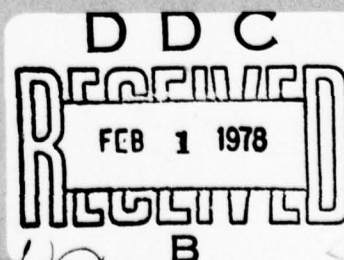HOUSING IN NORFOLK, VIRGINIA

May 1977

An Investigation Conducted by

SYSTEMS, SCIENCE AND SOFTWARE
La Jolla, California

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Air leakage measurements by the tracer dilution technique were conducted in two separate three-bedroom apartments in the Willoughby Bay housing area, Norfolk Navy Base, Norfolk, VA. Sulfur hexafluoride was used as the tracer gas, and the gas concentration was measured with a portable electron capture gas chromatograph at 10-minute intervals during two-hour test periods to determine dilution rates. Air change rates were deter-

over

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Block 20. Cont'd

mined directly from the logarithmic dilution rate of the tracer
gas. The procedures used were documented in detail for possible
incorporation into a field measurement procedure that is being
developed at the Civil Engineering Laboratory.

CONTENTS

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1. INTRODUCTION

Air leakage (infiltration) measurements in two separate three-bedroom apartment units of Chiefs' housing in the Willoughby Bay area of the Norfolk Navy Base were performed during the 9th, 10th and 11th of March 1977. One of the units had been resided with aluminum siding; the other had not.

The objectives of the measurement program were (1) to investigate and evaluate any difference in air leakage rate attributable to the presence or absence of aluminum siding, and (2) to design and test a field procedure for performing air leakage measurements in Navy apartment housing at Norfolk Navy Base.

Air leakage measurements by the tracer dilution method were performed using sulfur hexafluoride tracer gas and a portable electron capture gas chromatograph. Air leakage rates were measured with the HVAC system inoperative, and also operating. All measurements in this latter case were made from the outside of the structures. In addition, local meteorological data were obtained alongside the structures of interest.

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2. CONCLUSIONS

● The air leakage rates in the two apartments seem to be quite comparable (approximately 0.4 air changes per hour) in the case where winds are not directly head-on to the structure. In the case of winds blowing directly head-on to the structure, as opposed to coming from the side, the air leakage rate is apparently much higher (a factor of 2 in this case). Considering the orientation of the apartment complexes, and the location of the test apartments (in the center of the complex), for the full effect of wind to be felt, it must be coming from a northerly or a southerly direction. Winds from an easterly or westerly direction will be shielded by other apartments in the complex.

● The presence or absence of aluminum siding did not affect the measured air leakage on the days when winds were comparable in magnitude (~6 mph) and direction (easterly or westerly). However, due to the fact that both apartment units were shielded by other apartments from direct easterly or westerly winds, only northerly or southerly winds would impinge directly on the units being measured. Such meteorological conditions would provide a direct test of the effect of residing on air leakage. Unfortunately such winds did not prevail during the period of measurement. Hence the data are incomplete, as only one structure was tested during a wind which impinged directly on it.

● It appears possible to perform air leakage measurements in these apartments using the exterior ventilation system. Access to this system is from an external locked doorway. It appears that we will be able, at least in this area, to perform air leakage measurements in occupied structures from the outside and thereby cause a minimum of inconvenience or discomfort to the tenants.

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3. BACKGROUND

Air leakage (infiltration) represents an important part of the heating and cooling load of residential, commercial and industrial buildings. It is also an important parameter in indoor-outdoor air pollution relationships. The heat loss associated with air leakage through the enclosure of a typical house may be as much as 40 percent of the total heat load.[1]

Considerable energy savings can be realized by reducing the air leakage in a structure. Recently, a numerical simulation[2] of the heating requirements for a two-story residence conforming to a minimum FHA standard demonstrated that a 24% energy saving could be realized by reducing the air leakage 50% (from 1 to ½ air change per hour).

Air leakage (infiltration) is difficult to quantify because it is not only a function of building tightness and configuration, but also of inside-outside temperature differences, wind velocity and direction, and possibly other factors. Standard formulae do exist to estimate air-exchange rates[3] but they are at best rough approximations, since actual leakage rates often depend on non-calculable quantities such as the quality of workmanship in construction.

The tracer-dilution method has been used for a number of years to measure air leakage rates.[4-9] The technique entails introducing a small amount of tracer gas into a structure and measuring the rate of change (decay) in tracer concentration. The air change rate (generally air changes per hour, abbreviated ACPH) can be determined from the logarithmic decay rate of tracer concentration with respect to time.

In the present study sulfur hexafluoride (SF_6) was used as the tracer gas. It is odorless, colorless, nontoxic, detectable at very low concentrations, and is transported and dispersed as other atmospheric gases because of its high diffusivity.

The basic assumption underlying tracer-gas studies of air leakage is that the loss rate of tracer concentration conforms to the well-known exponential dilution law; i.e., the loss rate, or decay, of an escaping gas is proportional to its concentration. For any concentration, C, at time t, then

$$-dC/dt \sim C \quad \text{or} \quad -dC/dt = IC \tag{1}$$

where I is constant. From this one can formulate the following equation:

$$C = C_o e^{-It} \tag{2}$$

where C_o is the initial concentration of tracer gas when t = 0.

Expressed in slightly different terms, a loss in tracer gas concentration is equal to the product of the fraction of the gas which escapes and the concentration at the time of loss, or

$$-dC = (L/V) \, dt \, C , \tag{3}$$

where L = air leak rate, V = test volume, and C = tracer gas concentration during the interval dt. Note that L/V dt is the fraction of the air which escapes during the time dt. Comparing Equations (3) and (1), the exponential dilution law implies that I = L/V and that

$$C = C_o e^{-(L/V)t} . \tag{4}$$

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Here L/V is the air leakage rate, commonly given as ACPH. Equation (4) may be rewritten to give

$$I = L/V = 1/t \ln C_o/C \quad . \tag{5}$$

This equation is the theoretical basis of tracer studies of room and building air exchange.

Stated another way, we have shown that the air change rate in an enclosed space during a selected time interval is directly proportional to the natural logarithm of the ratio of the concentrations of the tracer gas at the beginning and end of the time interval, assuming that the forces causing infiltration remain constant. A constant infiltration rate is then represented by a straight line on semi-logarithmic paper.

Published information[5] on infiltration measurements in two test houses at the University of Illinois, one a two-story brick veneer structure over a basement and the other a one-story frame structure over a basement, indicated that the air change rate in each was directly proportional to the indoor-outdoor temperature difference and also to the wind velocity. These data showed that an increase in wind velocity of one mph was equivalent to an increase in indoor-outdoor temperature difference of 2 to 4°F in its effect on the infiltration rate. Thus, an expression of the form of Equation (6) can be used to approximate the effect of wind and temperature difference on the air change rate for a test house.[6] This is represented by

$$I = a + bW + cT \quad , \tag{6}$$

where I = infiltration rate (hourly air change rate), W = wind velocity (mph), T = inside-outside temperature difference (°F), a = the air change rate with no wind and

no temperature difference (hr^{-1}), and b,c = the increase in
the air change per unit increase in wind velocity and temp-
erature difference, respectively. Under field conditions, it
is difficult to isolate the effects of wind and temperature
without an extensive measurement program. However, Equation
(6) implies that upper bounds may be placed on infiltration
by performing measurements during those times in which wind
velocity or inside-outside temperature difference is the
greatest.

4. MEASUREMENTS AND DISCUSSION

The exact locations of the tested apartment structures are 8253 and 8422 O'Connor Crescent, in the Willoughby Bay area, and are shown in Figure 1. The apartment unit at 8253 had been recently retrofitted with aluminum siding and during the course of measurements was unfurnished and unoccupied. The unit at 8422 did not have aluminum siding and was occupied and furnished during the measurement interval.

It should be emphasized that no attempt was made to block obvious sources of leakage such as kitchen fans, bathroom vents, etc. During the period of measurement all exterior doors and windows were closed.

Also shown in Figure 1, and marked by a star with the letter "M" is the location of the meteorological station during the course of the air leakage measurements at the particular structure. All air leakage measurements were performed using SF_6 and the tracer dilution method. Measurements of SF_6 concentration were performed with a Systems, Science and Software Model 215AUP portable tracer gas monitor. Details of the use of this instrument and SF_6 in the performance of air leakage testing will be found in Appendix B. Meteorological data were monitored with a Meteorology Research Inc. mechanical weather station.

Two types of air leakage measurements were performed. In one, the so-called "free decay" type, SF_6 was injected into the HVAC system and uniformly dispersed throughout the structure using both portable fans and the HVAC system fan. The SF_6 was homogenized by using interior fans and the HVAC fan until SF_6 concentrations measured at various locations agreed to within 4%. At this time the HVAC fan was turned off and concentration decay monitored both upstairs and downstairs.
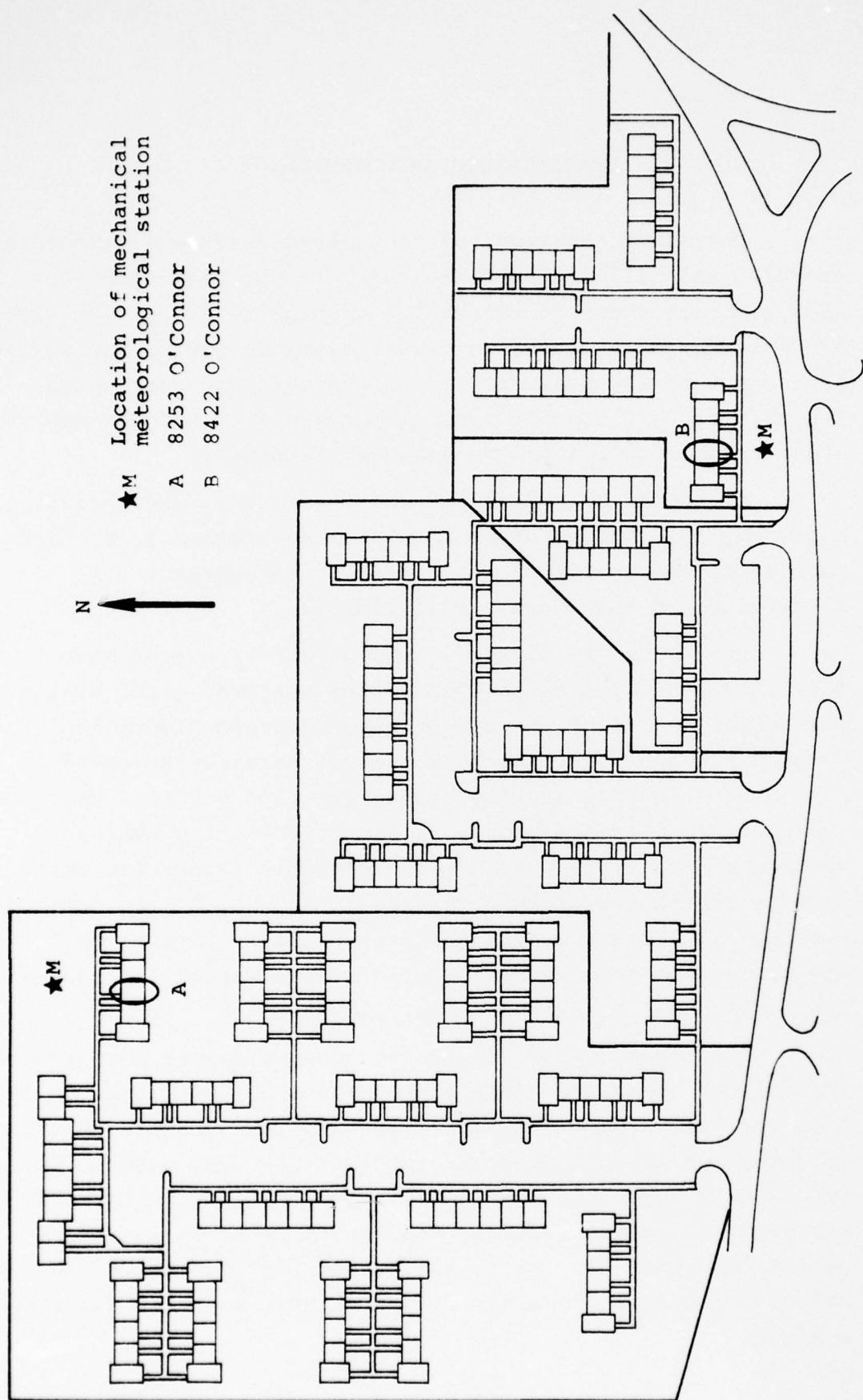
Legend:

★M Location of mechanical meteorological station

A   8253 O'Connor

B   8422 O'Connor

Figure 1. Plot plan of Willoughby Bay area showing location of test apartments and meteorological station.

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Figure 2 shows the floor plan of the three-bedroom apartment unit. Sample locations "A" on the first and second floor were the positions at which samples were drawn in the unit at 8253 O'Connor; sample locations "B" were the sampling locations for the unit at 8422 O'Connor.

Samples from the upstairs locations were drawn with disposable 12cc polyethylene syringes and injected into the monitor for analysis. Downstairs samples were drawn directly with the sampling pump contained in the monitor.

In order to perform the second type of leakage measurement, the "ventilation" type measurement, SF_6 was again introduced into the structure through the HVAC system ducting. SF_6 was injected into the ventilation duct from outside of the structure and the system allowed to run for some 30 to 45 minutes, at which time we assumed homogeneity. This assumption is supported by measurements previously made indoors which indicated an approximate 4% variation in SF_6 concentration.

The HVAC system was left running and concentration decay was monitored by drawing a sample from the ducting. Measurement samples were drawn using disposable 12cc polyethylene syringes from the ventilation duct and analyzed with the monitor.

SF_6 for test release was prepared by drawing 1 cc of pure SF_6 and 9 cc of ambient air into a 12 cc disposable polyethylene syringe. For the volume at the apartment units being measured, 6 to 10 cc of this mixture would provide an initial concentration of approximately 10^{-9} parts SF_6 in air. This is an ideal initial concentration for the S^3 monitor.

Tables 1, 2 and 3 contain the raw data taken on the 9th, 10th and 11th of March. In practice, with the S^3 unit, only the LED output and the time of measurement are recorded.

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SECOND FLOOR PLAN
SCALE 1/4" = 1'-0"
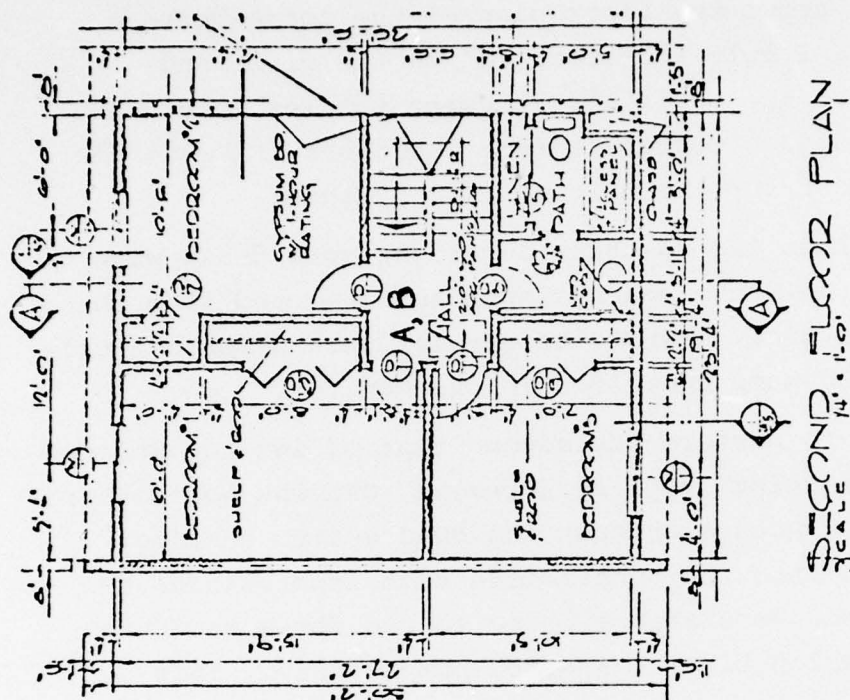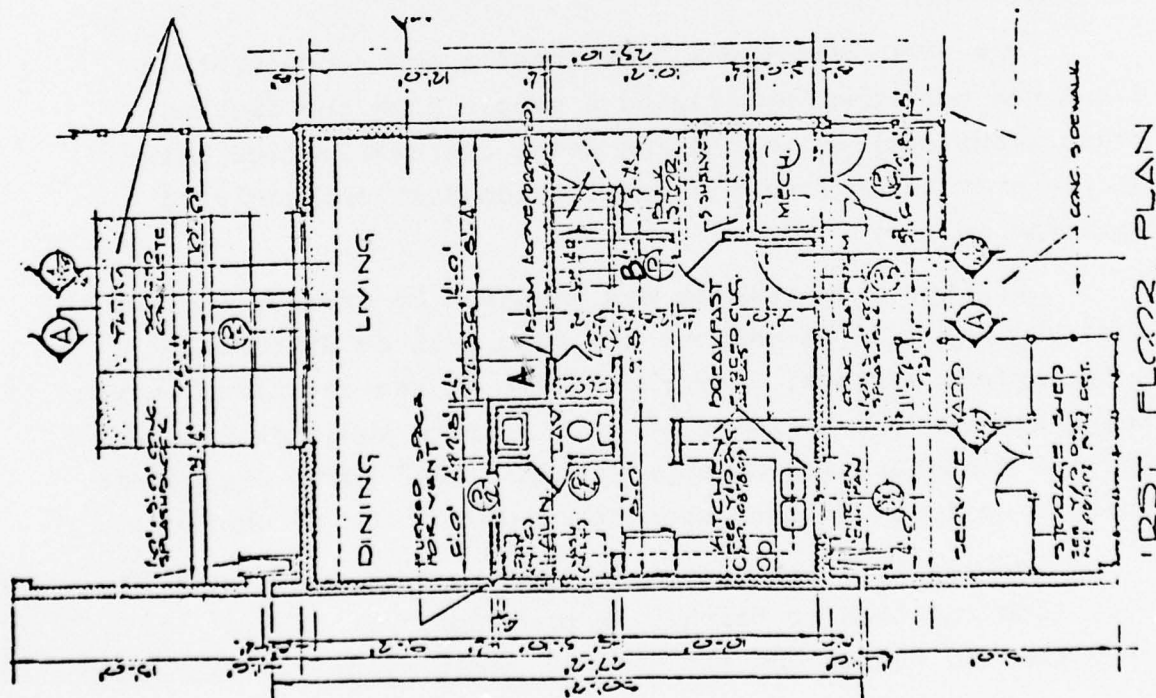
FIRST FLOOR PLAN

THREE BEDROOM UNIT

Figure 2. Floor plan of three-bedroom apartments showing sampling locations. Locations A are 8253 O'Connor and Locations B are 8422 O'Connor.

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Table 1. 8253 O'Connor Crescent. All data taken on "C" range. 9 March 1977

TIME	INSTRUMENT READING DOWNSTAIRS	ℓn O/100	INSTRUMENT READING UPSTAIRS	ℓn O/100
1010	789	2.0656	790	2.0669
1020	731	1.9892	741	2.0028
1030	666	1.8961	688	1.9286
1040	606	1.8017	631	1.8421
1050	555	1.7138	575	1.7492
1100	505	1.6194	525	1.6582
1110	460	1.5261	478	1.5644
1130	379	1.3324	396	1.3762
1140	345	1.2384	---	---
1150	303	1.1086	318	1.1569
1200	272	1.0006	---	---
1210	243	0.8879	254	0.9322
1220	216	0.7701	---	---
1230	193	0.6575	201	0.6981

*   *   *   *   *   *   SECOND RUN   *   *   *   *   *   *

TIME	INSTRUMENT READING DOWNSTAIRS	ℓn O/100	INSTRUMENT READING UPSTAIRS	ℓn O/100
1420	577	1.7527	562	1.7263
1430	503	1.6154	503	1.6154
1440	445	1.4929	456	1.5173
1450	398	1.3813	411	1.4134
1500	385	1.2754	374	1.3191
1510	324	1.1756	340	1.2238
1520	296	1.0852	309	1.1282
1530	266	0.9783	279	1.0260
1540	240	0.8755	253	0.9282
1550	217	0.7747	---	---
1600	191	0.6471	201	0.6981
1610	---	---	---	---
1620	151	0.4121	159	0.4637
1630	134	0.2927	---	---
1640	121	0.1906	127	0.2390
1650	102	0.0198		

Table 2. 8422 O'Connor Crescent. All data taken on "C" range. 10 March 1977

TIME	INSTRUMENT READING DOWNSTAIRS	ln O/100	INSTRUMENT READING UPSTAIRS	ln O/100
0910	845	2.1342	827	2.1126
0920	747	2.0109	759	2.0268
0930	682	1.9199	708	1.9573
0940	644	1.8625	665	1.8946
0950	607	1.8034	631	1.8421
1000	580	1.7579	595	1.7834
1010	561	1.7246	566	1.7336
1020	531	1.6696	534	1.6752
1030	501	1.6114	---	---
1040	470	1.5476	479	1.5665
1050	445	1.4925	449	1.5019
1100	423	1.4422	428	1.4540
1110	407	1.4036	408	1.4061
1120	396	1.3762	388	1.3558
1130	381	1.3376	365	1.2947

* * * * * VENTILATION SAMPLE TEST * * * * * * * *

TIME	INSTRUMENT READING IN DUCT (O)	ln O/100
1330	489 x 2 (978)	---
1340	842	2.1306
1350	761	2.0295
1400	692	1.9344
1410	625	1.8326
1420	564	1.7299
1430	513	1.6351
1440	467	1.5412
1450	425	1.4469
1500	382	1.3403
1510	354	1.2641
1520	323	1.1725
1530	295	1.0818

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Table 3. 8253 O'Connor Crescent. All data taken on "C" range. 11 March 1977

TIME	INSTRUMENT READING IN DUCT (O)	ℓn O/100
0855	344 x 2 (688)	1.9286
0900	627	1.8358
0910	575	1.7492
0920	521	1.6506
0930	474	1.5560
0940	427	1.4516
0950	383	1.3429
1000	347	1.2422
1010	307	1.1217
1020	271	0.9969
1030	244	0.8920
1040	219	0.7839
1050	193	0.6575
1100	172	0.5423

* * * * * * * * * AFTERNOON INSIDE TEST * * * * * * *

TIME	INSTRUMENT READING DOWNSTAIRS	ℓn O/100	INSTRUMENT READING UPSTAIRS	ℓn O/100
1305	524 x 2(1048)			
1315	464 x 2 (928)			
1320	834	2.1211	848	2.1377
1330	790	2.0669	805	2.0857
1340	749	2.0136	765	2.0347
1350	726	1.9824	724	1.9796
1400	696	1.9402	690	1.9315
1410	656	1.8810	659	1.8856
1420	620	1.8245	621	1.8262
1430	586	1.7681	588	1.7716
1440	553	1.7102	553	1.7102
1450	517	1.6429	528	1.6639
1500	490	1.5892	494	1.5974

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One can, at a later time, convert the instrument readings to SF_6 concentration. However, as is shown in Appendix A this conversion is not necessary; the LED reading and the slope of the calibration curve is sufficient. Also presented is the natural logarithm of the LED output value — denoted "O" — divided by 100. The use of this column of numbers is discussed below.

When calculating air leakage rates it is conventional to use Equation (5) in graphical form. The simplest way to get the air change rate is by plotting, not the concentrations or the numbers proportional to the concentrations, but the natural logarithm of these units as a function of time. Simple differencing allows one to infer air change rates. In practice, finding the logs of larger numbers (say in the hundreds) usually necessitates interpolating a table of logarithms. Since we are interested only in ratios, the actual LED outputs can be divided by any common divisor which may be convenient. If we choose to divide the output values by 100, then a few pages in a table of logarithms provides all the conversions we need. It should be emphasized that division of the LED output by 100 is solely for numerical convenience.

In Figures 3 and 4 we show the measurements for the structures at 8253 and 8422 O'Connor Crescent. In these plots time is in minutes starting from the onset of a given test. LED output is plotted directly as the natural log of the output divided by 100. As is evident from these figures, the log of the concentration does decay in a linear fashion with time. There are slight aberrations and departures from strict linearity but these are small, as can be seen by studying the figures.

Table 4 presents meteorological data taken with the portable meteorological station adjacent to the test structures.
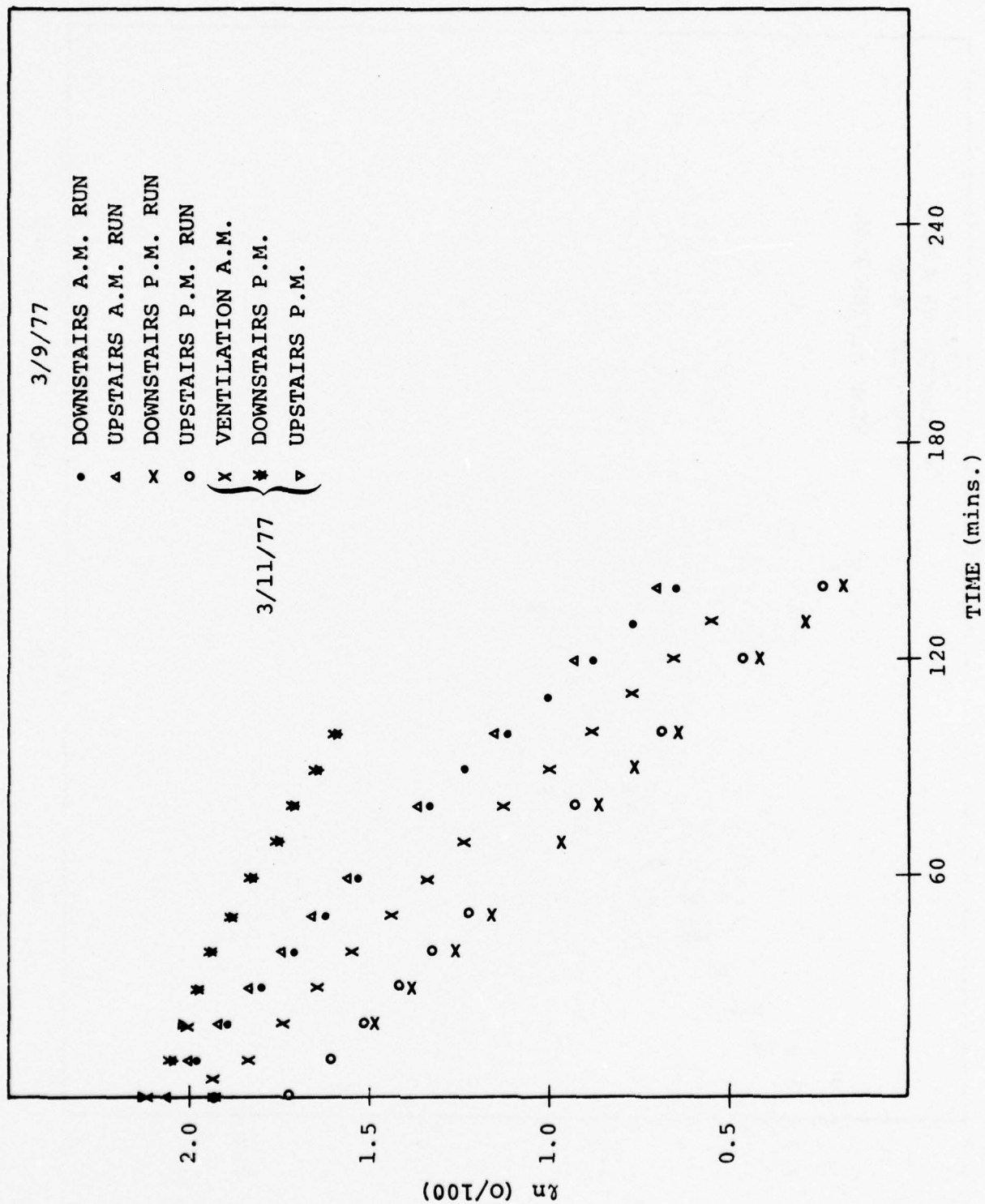
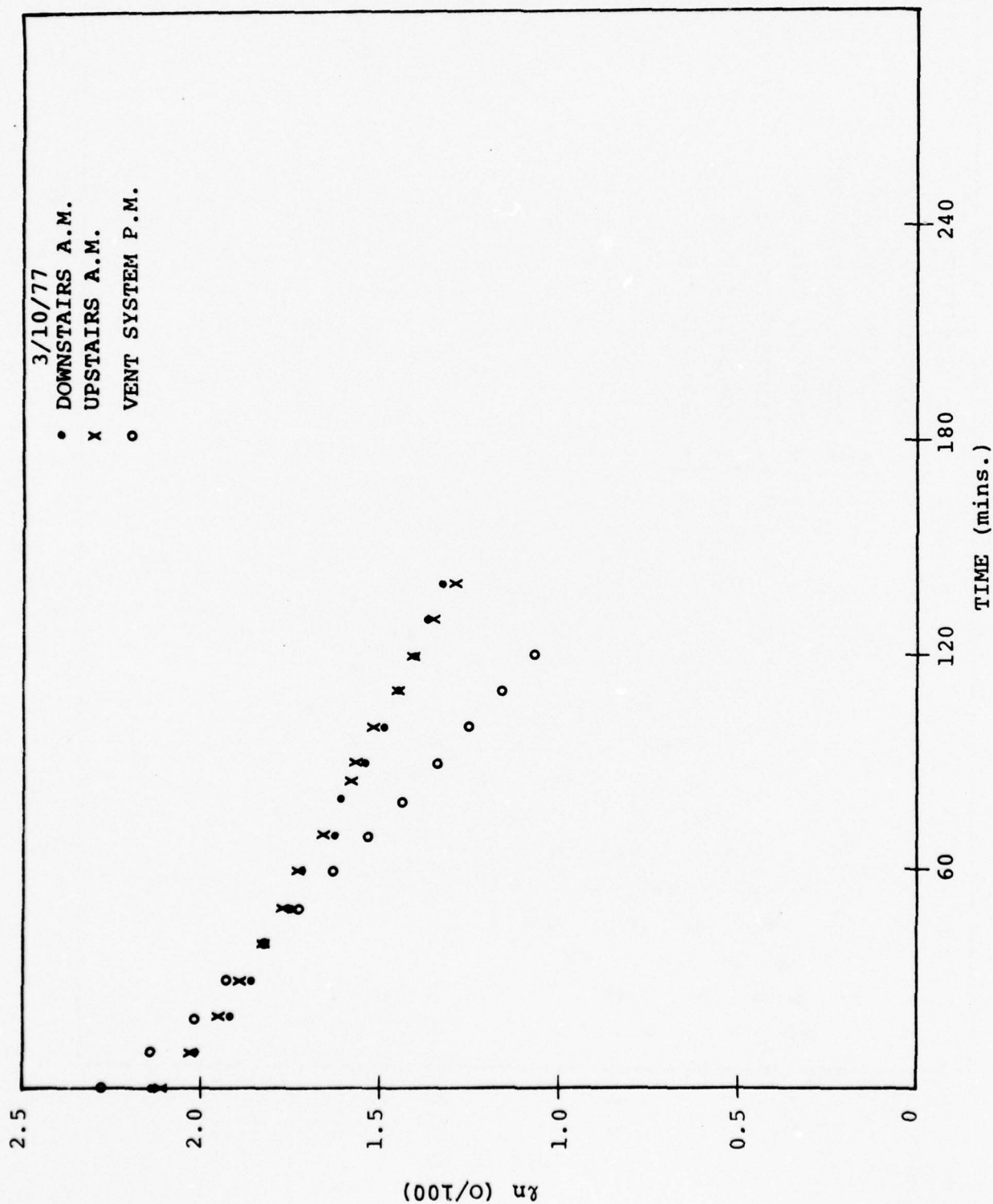Figure 3. Concentration decay data at 8253 O'Connor Crescent.

Figure 4. Concentration decay at 8422 O'Connor Crescent.

Table 4. Meteorological data.

DATE	TIME	OUTSIDE TEMP. (°F)	AVERAGE WIND SPEED (mph)	AVERAGE WIND DIRECTION
3-9	0900	47	6.0	210
	0930	50	6.0	210
	1000	52	6.0	210
	1030	53	5.6	210
	1100	56	6.0	210
	1130	58	6.5	210
	1200	60	6.8	210
	1230	62	6.7	210
	1300	62	7.2	210
	1330	63	7.6	210
	1400	64	7.8	210
	1430	65	8.2	210
	1500	65	7.9	210
	1530	65	7.3	210
	1600	65	7.2	210
	1630	64	6.2	210
	1700	61	--	210
3-10	0900	53	--	230
	0930	53	6.5	230
	1000	55	5.0	230
	1030	58	5.5	230
	1100	60	6.0	230
	1130	57	5.0	270
	1200	58	4.0	270
	1230	60	3.0	270
	1300	55	3.0	60
	1330	55	3.5	60
	1400	58	3.0	30
	1430	57	3.0	60
	1500	56	3.0	60
	1530	57	--	60
3-11	0830	54	--	90
	0900	51	6.5	90
	0930	51	6.0	70
	1000	52	6.2	70
	1030	50	--	60
3-11	1300	57	--	60
	1330	56	8.8	80
	1400	56	9.2	90
	1430	56	10	90
	1500	54	--	70

Wind speeds are measured to ~±5%, while wind direction is
uncertain by ±15°. Table 5 shows indoor temperatures which
were taken from the thermometer located on the thermostats
in the structures being measured. The indoor and outdoor
temperatures plotted as a function of time, where 0 minutes
is 0800 on the day of interest, are plotted in Figure 5.

The infiltration data are summarized in Table 6.
Air change rates for upstairs and downstairs are shown since
there was an apparent small difference in the measured rates
in several cases. A mean is given which is the volume-
averaged value of the upstairs and downstairs rates. Also
indicated are air change rates as measured from the venti-
lation system. In addition average values for indoor-outdoor
temperature, wind speed and wind direction are presented.

Several very interesting points appear in this table.
The free decay air leakage rates, in both of the test struc-
tures, are comparable under the condition in which the winds
are not blowing head-on to the apartment complexes. In the
case of wind blowing head-on (SSW) to the structure at 8253
we find that the infiltration rate was almost a factor of
2 higher than for a case where the wind is not directly
impinging on the structure. Reference to the meteorological
data shows that the wind on the 9th was predominantly from
the south to southwest, whereas the winds on the 10th and
11th were primarily easterly or westerly. Their magnitudes
are comparable.

Another finding is that we are able to measure a
leakage rate using only the ventilation system. This rate
is higher than the free decay air change rate. Theoretically
the two methods will agree if there is no "make-up" air
drawn into the HVAC system, and if the HVAC system does not
overpressure the structure and create an additional pressure
driven leakage. Reference to Figures 3 and 4 shows that the

Table 5. Inside temperatures.

DAY	TIME	TEMPERATURE (°F)
3-9	0917	62
	1012	67
	1135	72
	1229	73
	1354	73
	1453	73
	1532	71
	1622	69
	1655	68
3-10	0844	68
	0942	69
	1116	71
3-11	0830	61
	1015	69
	1251	75
	1402	74
	1500	73

Table 6. Summary of Infiltration Measurements.

DATE	TIME	LOCATION	AIR CHANGE RATE WITH VENTILATION SYSTEM INOPERATIVE		AIR CHANGE RATE WITH VENTILATION SYSTEM OPERATING	MEAN	TEMPERATURE DIFFERENCE (°F)	WIND SPEED+ (mph)	WIND DIRECTION* (°)
			DOWNSTAIRS	UPSTAIRS					
3/09/77	A.M.	8253 O'Connor Crescent	0.75	0.75	--	0.75	11°	6.0	210
3/09/77	P.M.	8253 O'Connor Crescent	0.80	0.74	--	0.77	9°	7.5	210
3/10/77	A.M.	8422 O'Connor Crescent	0.36	0.40	--	0.38	15°	5.5	230
3/10/77	P.M.	8422 O'Connor Crescent	--	--	0.69	0.69	15°	3.2	60
3/11/77	A.M.	8253 O'Connor Crescent	--	--	0.82	0.82	15°	6.2	70
3/11/77	P.M.	8253 O'Connor Crescent	0.39	0.40	--	0.40	18°	9.4	75

+ Uncertainty of ±5%

* Uncertain by ±15°

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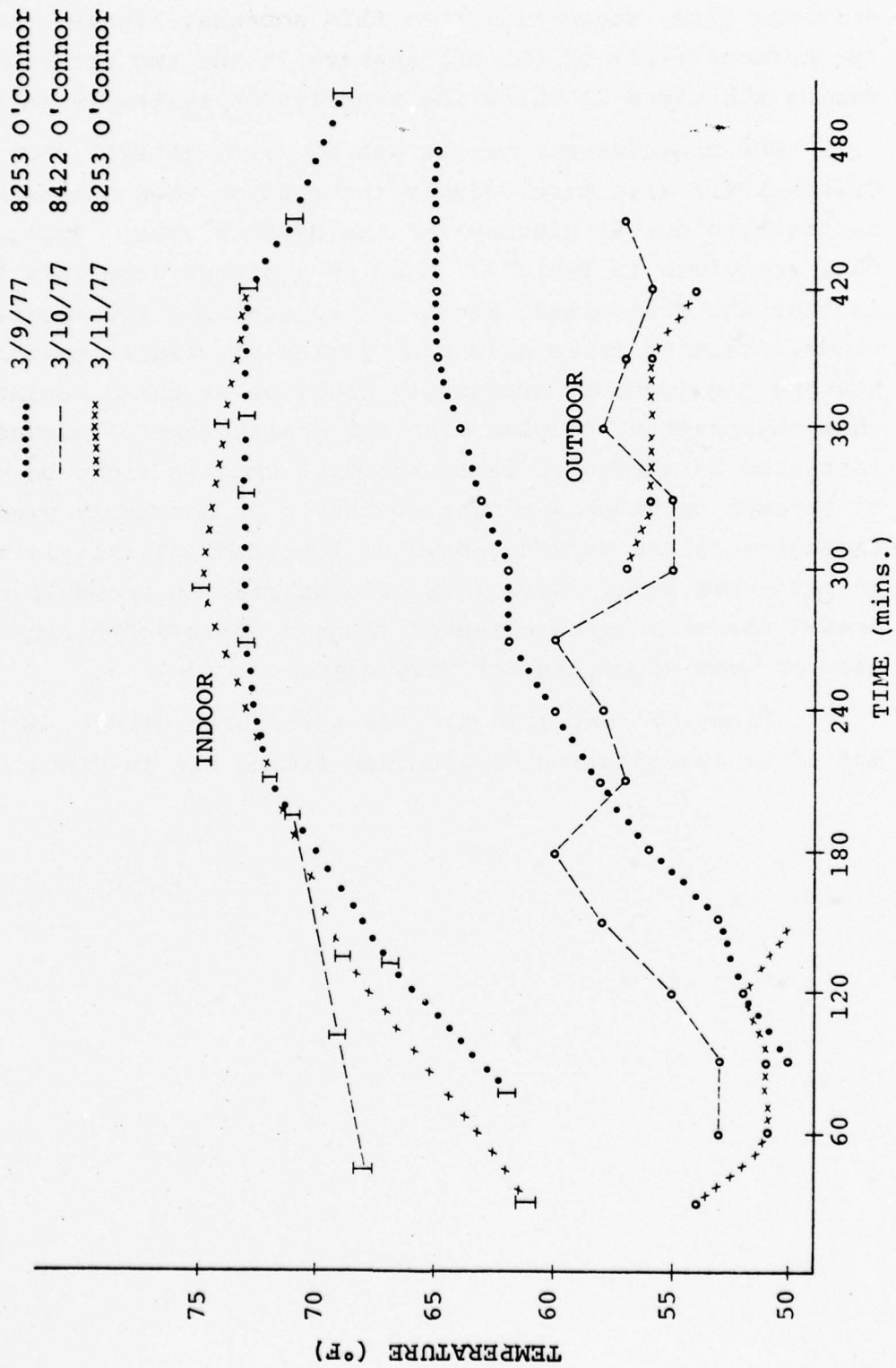
Figure 5. Indoor and outdoor temperatures.

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logarithms of the concentrations do fall on a relatively straight line, suggesting that this somewhat higher number is characteristic of the air leakage in the two structures during the times in which the ventilation system is in use.

The measurements on the 9th of March at 8253 O'Connor Crescent are also particularly interesting when one examines the meteorological history for the Norfolk area. Typical data are given in Table 7. What is apparent from this table is that the predominant winds in the area are southwesterly winds. This is especially true during the winter months when heating requirements presumably would be at their maximum. This observation, coupled with the measurement of markedly increased infiltration rate, suggests that it might be useful to attempt to block a direct southerly or northerly wind from impinging on the structures whose longitudinal axis is along an east-west line. Some form of windbreak is probably not needed for structures oriented along a north-south line since east or west winds are not very common.

Views of test area and the structures before, during, and after installation of aluminum siding are in Plate 1.
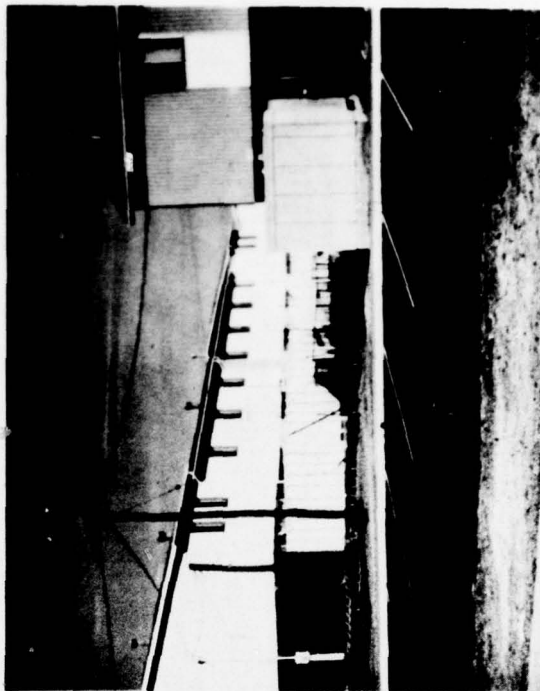
APARTMENT TESTED BEFORE INSTALLATION
OF ALUMINUM SIDING. METEOROLOGICAL
STATION USED IS SHOWN AT LEFT.

OVERALL VIEW OF APARTMENTS (LEFT SIDE)
AFTER INSTALLATION OF ALUMINUM SIDING.
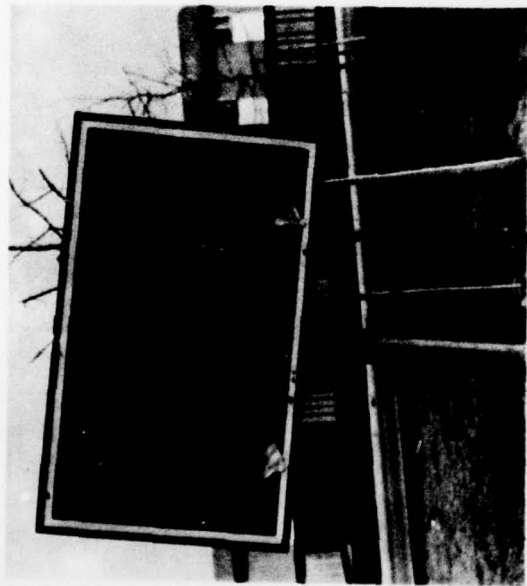
IDENTIFICATION OF
TEST AREA

CLOSE-UP OF APARTMENTS DURING
INSTALLATION OF ALUMINUM SIDING.

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Normals, Means, And Extremes

Table 7. Meteorological data for Norfolk, Virginia.

RECOMMENDATIONS

● Infiltration measurements should be performed in
several additional structures which are similar to the two
investigated in this study to determine if the difference bet-
ween free mode and ventilation mode air leakage measurements
has a consistent relationship with the two structures measured.
If so, this would strengthen the argument for using ventila-
tion mode measurements to characterize air leakage. One
could then get the free decay by subtracting an approximate
differential value.

● During the course of ventilation mode air leakage
measurements in these structures the pressure difference between
the inside and outside should be measured to determine if the
increase in air leakage rate observed during ventilation mode
measurements is due to overpressuring of the structure. If
it is, this measurement will allow us to correlate the degree
of overpressure with the increase in ventilation mode air
leakage.

● Air leakage data should be obtained in several struc-
tures over a range of climatological conditions in order to
allow a realistic air leakage algorithm to be developed which
would apply to all housing at the Norfolk Navy Base.

● Air leakage measurements should be made in several of
these apartment structures when the wind is head-on to the
unit being measured. Along this same vein, investigation of
the directional nature of this air leakage rate could be
performed by utilizing simultaneous measurements in several
structures which bear different orientations to prevailing
wind. In this way one would be able to develop a firmer
understanding of the directional effect of wind on the air
leakage in these apartment units.

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APPENDIX A

In Figure A-1 we show a typical calibration curve of the S^3 Model 215AUP portable tracer gas monitor. A salient feature to observe is the fact that the calibration curve to convert LED output to SF_6 concentration is a straight line. Mathematically this means that we can write an equation of the form

$$\ln C = A \ln 0 , \tag{A1}$$

where $C = SF_6$ concentration, 0 = LED output value, A = the constant of proportionality which converts LED output to SF_6 concentration.

To calculate infiltration rate we use an equation of the form

$$I = 1/t \; \ln C_o/C . \tag{A2}$$

If we then have two measurements, or more, taken with the instrument and the calibration curve we have points which we can denote by

$$\ln C_o = A \ln 0_o ,$$

and

$$\ln C_t = A \ln 0_t . \tag{A3}$$

Then if we form the ratio of these as required by equation

$$I = \frac{1}{t} (\ln C_o - \ln C) = \frac{1}{t} (A \ln 0_o - A \ln 0_t) = \frac{A}{t} \ln \frac{0_o}{0_t} \tag{A4}$$

we find that the constant of proportionality, i.e., the calibration constant, enters linearly. This is the theoretical basis for the previous assertion that it is sufficient to plot the LED output values and not bother with the direct conversion to SF_6 concentration. To get true ACPH values, one need only multiply the LED output by the scale factor A. For the S^3 monitor used A = 1.21 ± 0.02.
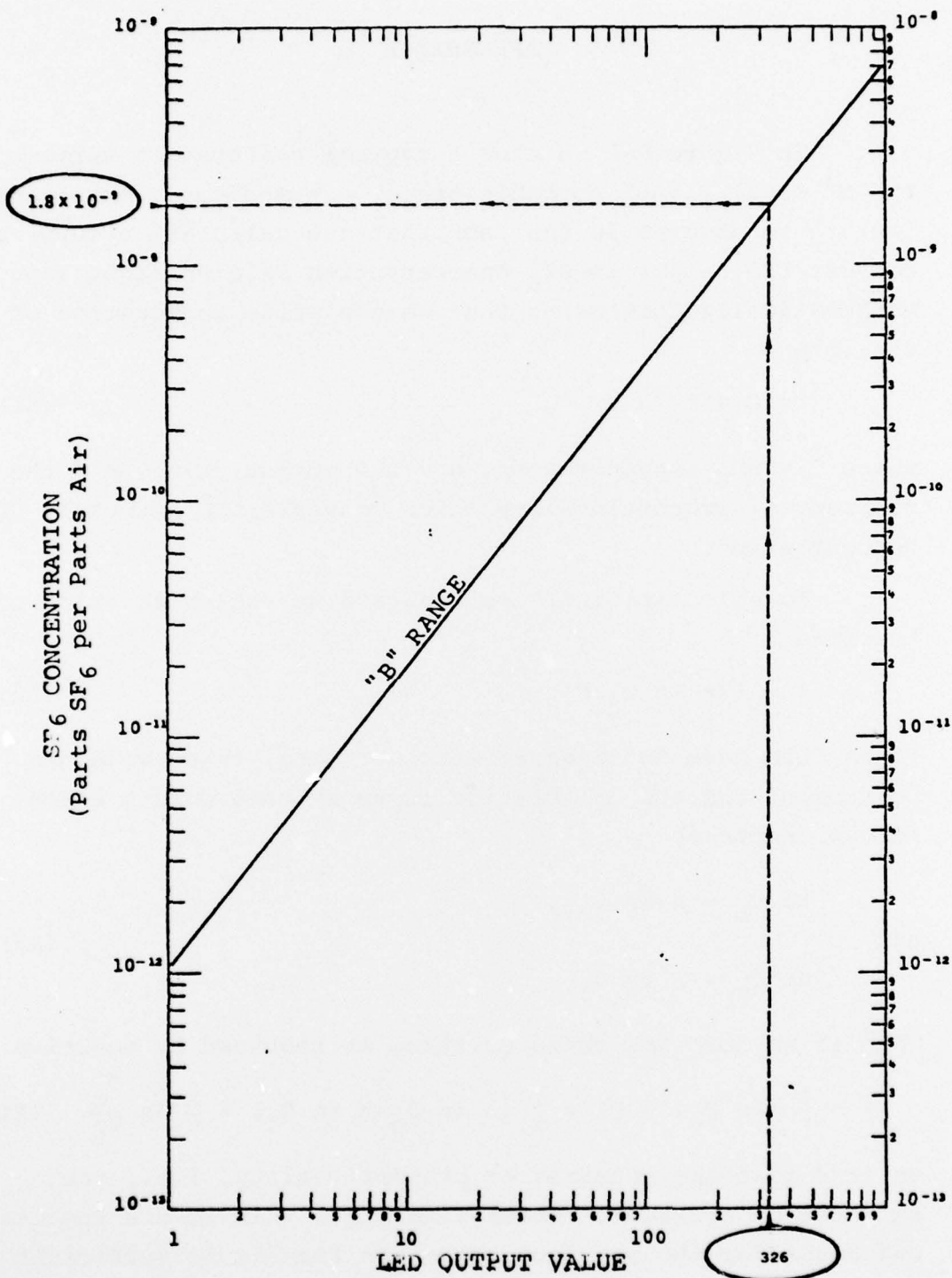
Figure A-1.   Example calibration plot for S³ Model
215AUP envirometer.

APPENDIX B

This appendix contains details on the use of the Systems, Science and Software Model 215AUP tracer gas monitor in conjunction with sulfur hexafluoride for the performance of air leakage testing. As discussed in the text of this report, air leakage testing is effected by introducing a small amount of sulfur hexafluoride into a structure of interest, homogenizing the concentration of SF_6 throughout the structure and then monitoring the logarithmic dilution of the sulfur hexafluoride concentration as a function of time. From this logarithmic dilution one can infer an air leakage rate. This technique is summarized graphically in Figure B-1.

Procedurally, the C or D ranges of the S^3 instrument are useful. Reference to Figure B-2 indicates that C and D ranges have linear response from about 10^{-9} parts SF_6 to 10^{-11} or 10^{-12}. In practice, one would like to introduce a sufficient quantity of SF_6 into a structure to allow the initial concentration to be somewhere on the order of a few parts in 10^{-9}. In this way one can begin air leakage measurements at the high end of a measurement range and then if necessary, follow this decay over many hours, should such a test be desired. Normally we find that use of the C range with initial concentrations corresponding to LED outputs between 600 and 800 yields sufficient data for normal infiltration type measurements. Starting near the high end of a given range on the instrument allows one to make measurements over many hours without having to change ranges in the course of performing measurements. This of course simplifies the data reduction since only a single range on the LED output is involved.

HIGHLY DILUTED TRACER GAS OUT

TRACER GAS RELEASED AND MIXED WITHIN STRUCTURE
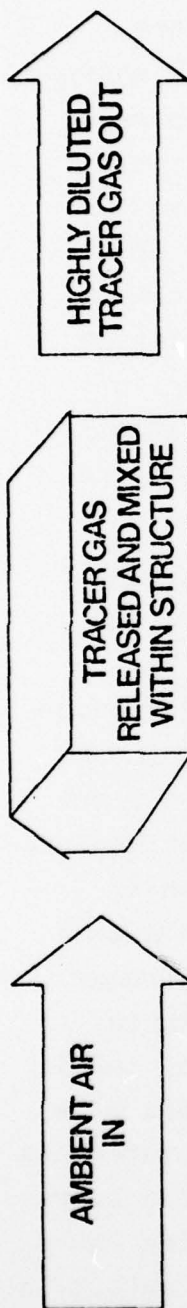
AMBIENT AIR IN

RATIO OF TRACER GAS TO AIR DECREASES IN STRUCTURE OVER TIME, BECAUSE INCOMING AMBIENT AIR HAS NO TRACER IN IT. THEREFORE, DECAY OF TRACER CONCENTRATION FOLLOWS THE LAW

$$C = C_o e^{-It}.$$

• MEASURE TRACER DILUTION (QUANTITATIVELY DETERMINE TRACER GAS CONCENTRATION OVER TIME) MEASURE C_o, C_t, t AND SOLVE FOR I

• CALCULATE RATE OF AIR CHANGE PER HOUR (ACPH = INFILTRATION RATE)
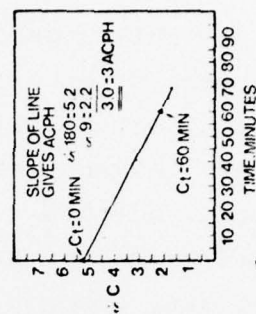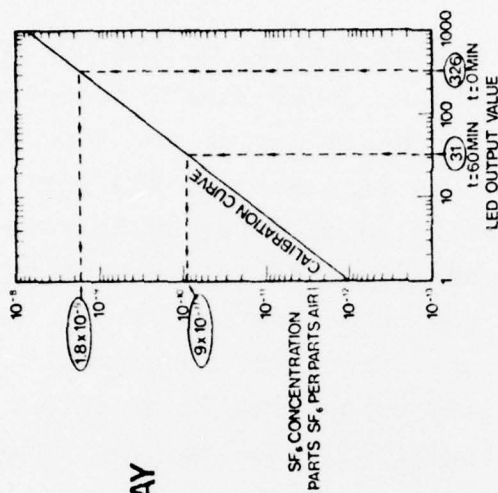
$$ACPH = \frac{1}{t} \ln C_o/C_t$$

SUPPRESS EXPONENT BY NOTING

$\ln 1.8 \times 10^{-9} = \ln 180 \times 10^{-11} \approx \ln 180 = 5.2$
(time = 0)

$\ln 9 \times 10^{-11} = \ln 9 \times 10^{-11} \approx \ln 9 = 2.2$
(time = 60)

t = 60 MIN − 0 MIN = 60 MIN = 1 HOUR

CALIBRATION CURVE

SF$_6$ CONCENTRATION (PARTS SF$_6$ PER PARTS AIR)

LED OUTPUT VALUE

1.8×10^{-9} 9×10^{-11} 31   326   t = 60 MIN   t = 0 MIN

SLOPE OF LINE GIVES ACPH

$\ln 180 = 5.2$ C$_t$ = 0 MIN
$\ln 9 = 2.2$ 3.0 = 3 ACPH

C$_t$ = 60 MIN

TIME: MINUTES
10 20 30 40 50 60 70 80 90

Figure B-1.   Tracer Dilution Method for inferring air change rate.
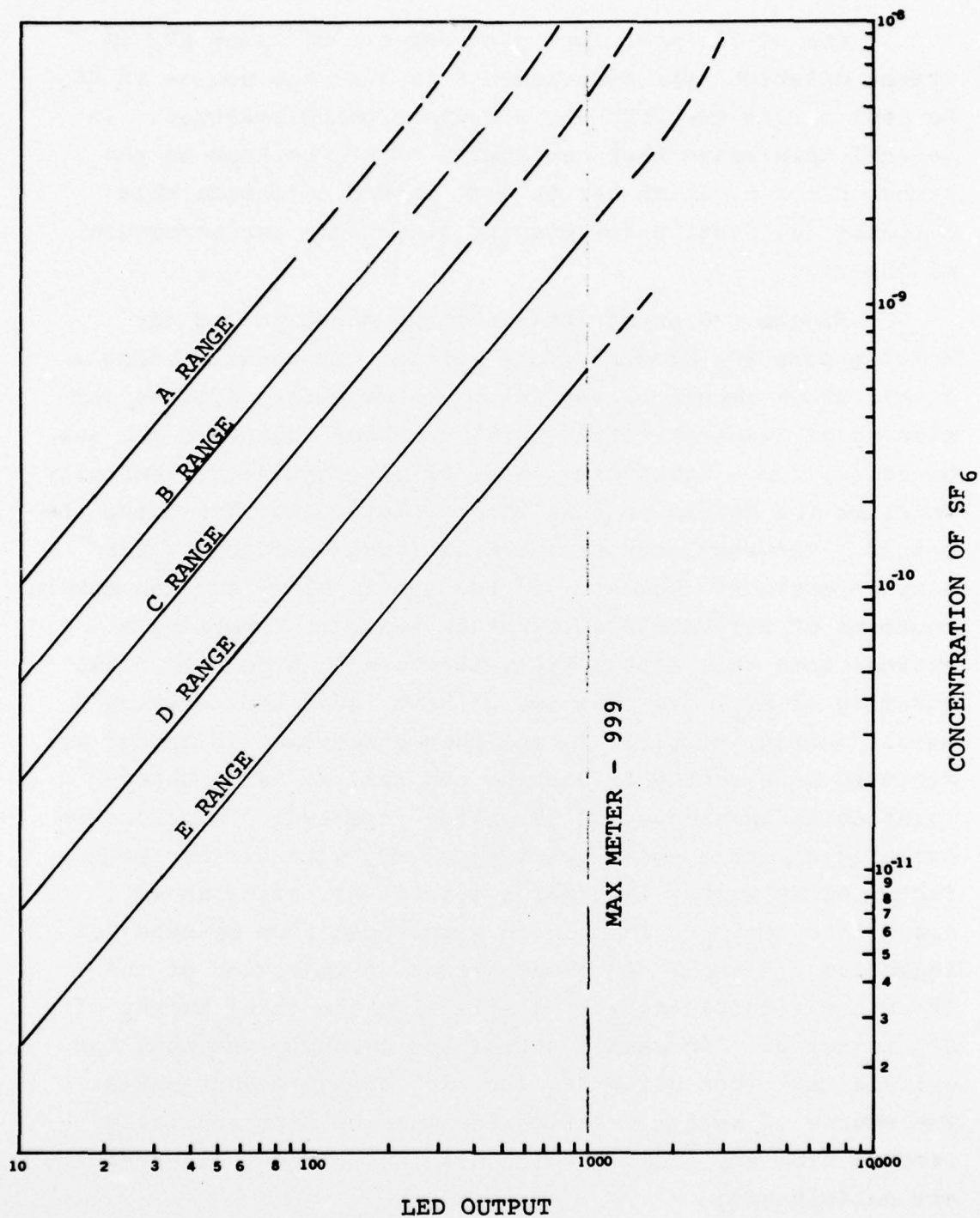
34

Figure B-2. Typical calibration curve for Model 215AUP
Envirometer.

One of the most important aspects of using SF_6 in tracer dilution type measurements is that the source of SF_6 be kept a long way from any structure being measured. In general this means that the source of SF_6 be kept in the trunk of a car, which car is kept parked a considerable distance (at least a few hundred feet) from any structure of interest.

Figure B-3 shows the technique which we use for drawing pure SF_6 from a supply bottle. It entails using a single stage regulator set for 5 pounds with a fitting consisting of Swagelok fitting with a rubber septum on the low pressure, i.e., downstream, side of the regulator. Normally we crack the bottle to fill the regulator and then close the bottle. The regulator plenum will retain enough SF_6 for many injections. However, if the septum blows out the entire contents of the bottle will not be vented. Inserting a syringe into this septum will allow one to draw some small quantity of SF_6. In practice we have found that drawing a small quantity of pure SF_6 and then attempting to inject it directly into tubing or ducting can lead to large uncertainties in the amount of SF_6 being injected. Therefore we normally dilute a small quantity of SF_6 with air by about a factor of 10 merely by drawing outside air after we've drawn 1 cc of SF_6. This 10 cc sample can then be used for injection. A small percentage error in injection of the 10 cc has significantly less effect on the total amount of SF_6 injected. One cannot stress too strongly the need for extreme care when using SF_6 for air leakage measurements. The source of sulfur hexafluoride must be kept spacially removed from any area in which meaningful decay measurements are anticipated.

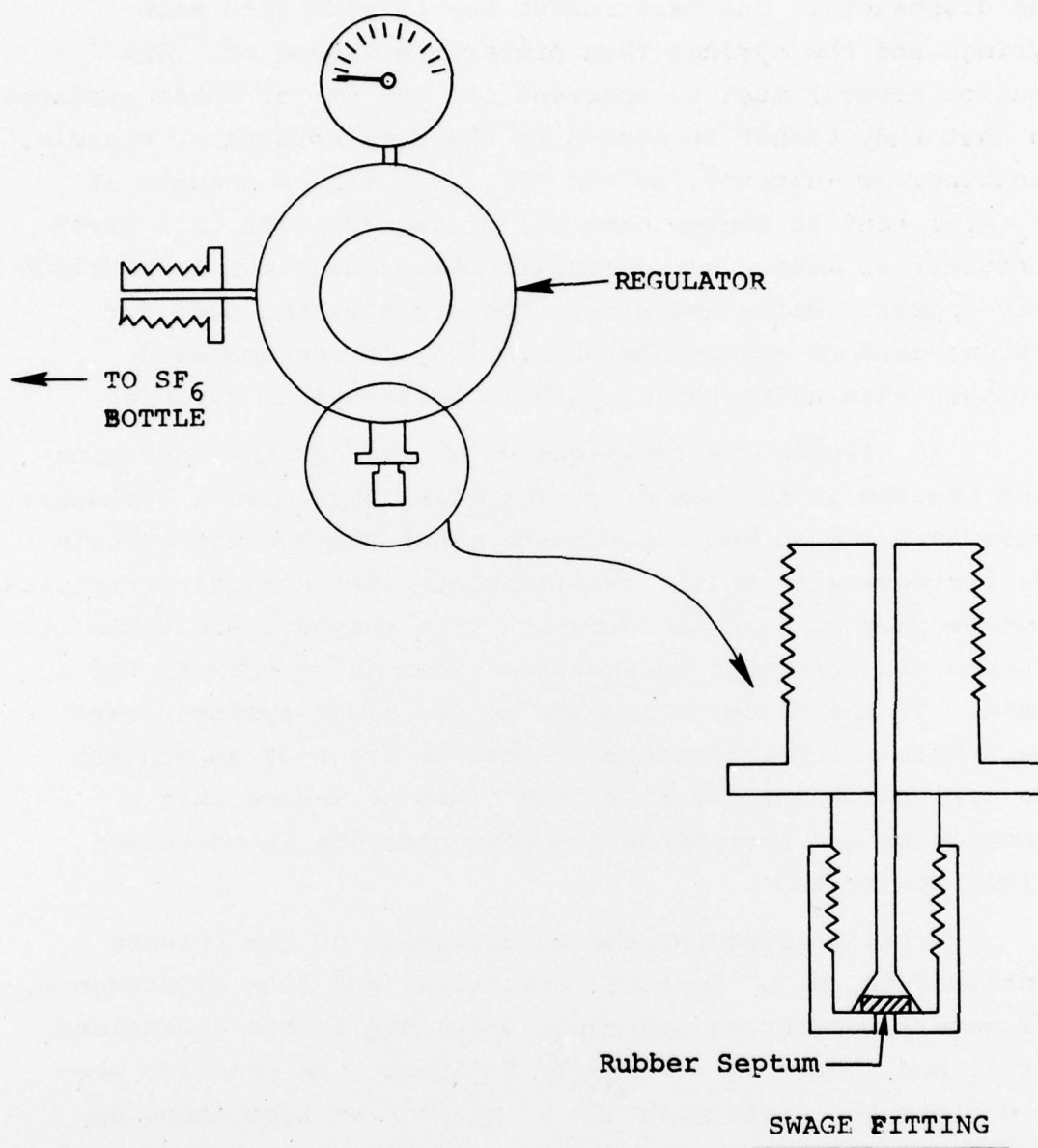We have found the use of 12 cc polyethylene syringes to be ideal. They are cheap (costing less than 20¢ apiece)

REGULATOR

TO SF$_6$
BOTTLE

Rubber Septum

SWAGE FITTING

Figure B-3. Regulator with septum for withdrawing
SF$_6$ samples from a gas bottle.

and disposable. One measurement may be made with each
syringe and the syringe then properly disposed of. One
caution however must be observed in the use of these syringes
in that they cannot be stored in the same structure, vehicle,
container or whatever, as the SF_6; even minute amounts of
SF_6 will tend to contaminate all of the syringes in a given
container no matter how elaborate the precautions to preclude
this appear. We cannot stress too strongly the need for
extreme care to reduce the possibility of contaminated
syringes when using the disposable polyethylene syringes.

An alternative technique which reduces the contamina-
tion problem is the use of ground glass physician's syringes.
These syringes do not contaminate since they do not contain
plasticizers with sulfur hexafluoride-like chemical structures.
However they do have the drawback that they are breakable if
dropped and care must be exercised when using them in the
field. If the decision is made to use glass syringes each
new sample which is injected should be drawn by aspirating
the syringe rapidly four or five times to insure that a
homogeneous and representative concentration is contained
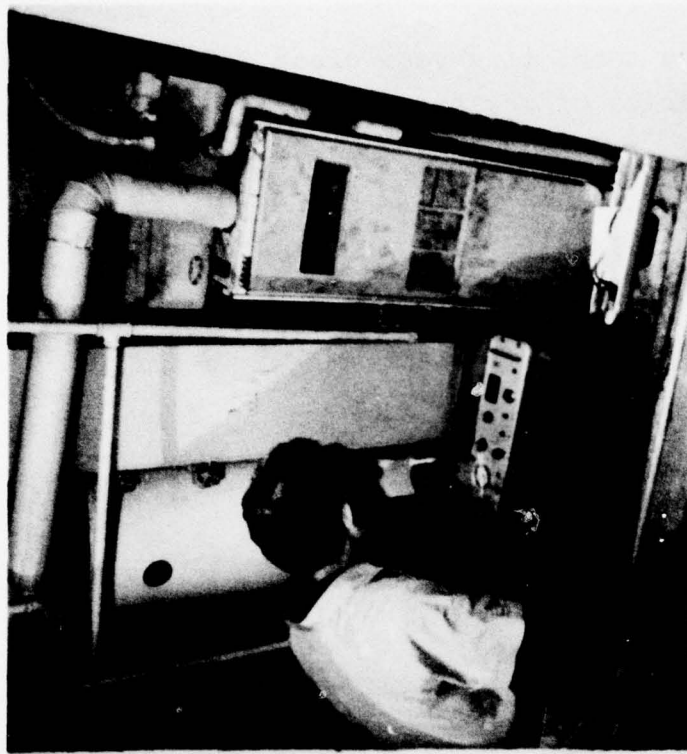within the syringe.

Details regarding the conditioning of the columns
contained in the S^3 monitor, electrical and flow adjustments,
and general operating procedure are given in the operations
manual and should be rigorously followed. In practice when
we go into the field with the S^3 monitor we take along an
additional supply of nitrogen in addition to that contained
in the on-board carrier supply. We use this to allow the
machine to continue to purge, i.e., to allow nitrogen to
keep flowing through the system even when the instrument is
not in use. In this way a properly conditioned column in
an instrument can be left purging overnight and will be ready
to make measurements without delay on the following day.

Such preplanning tends to save a great deal of time when initiating a series of measurements.

Views of SF_6 being injected into the apartments HVAC system, and of injecting an air sample into the chromatograph are in Plate 2.

INJECTION OF AIR SAMPLE (DRAWN FROM HVAC RETURN DUCT) INTO CHROMATOGRAPH FOR SF_6 CONCENTRATION MEASUREMENT.

INJECTION OF SF_6 INTO HVAC SYSTEM FOR DISPERSION THROUGHOUT THE APARTMENT.